RESEARCH MEMORANDUM

FUNDAMENTAL FLAME VELOCITIES OF PURE HYDROCARBONS

III - EXTENSION OF TUBE METHOD TO HIGH FLAME VELOCITIES - ACETYLENE-AIR MIXTURES

By Oscar Levine and Melvin Gerstein

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

December 3, 1951

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

FUNDAMENTAL FLAME VELOCITIES OF PURE HYDROCARBONS

III - EXTENSION OF TUBE METHOD TO HIGH FLAME VELOCITIES - ACETYLENE-AIR MIXTURES

By Oscar Levine and Melvin Gerstein

SUMMARY

The tube method of measuring flame velocities has been extended to fundamental flame velocities of 141 centimeters per second. This extension was accomplished by reducing the flame-tube diameter from 25 to 12.5 millimeters. The reduction in flame-tube diameter decreased the Reynolds number of the unburned gas ahead of the flame from a turbulent to a laminar region. The gas-velocity correction in the 12.5-millimeter flame tube fits the empirical linear relation between gas velocity and spatial flame velocity previously obtained in the 25-millimeter flame tube. The ratio of the flame-tube cross-sectional area to the flame surface area was found to be the same constant in the 25- and the 12.5-millimeter flame tubes. A simplified equation for calculating the flame surface area from flame photographs is presented.

The maximum fundamental flame velocity of acetylene-air mixtures was found to be 141 centimeters per second, which is in satisfactory agreement with Bunsen burner results.

INTRODUCTION

A program to study the effect of different fuel properties on combustor performance is in progress at the NACA Lewis laboratory. One phase of this program has been to determine the effect of molecular structure on the rate of flame propagation through combustible mixtures of pure hydrocarbon and air (references 1 to 3). Inasmuch as many of the hydrocarbons of interest are available only in very limited quantities, a tube method that utilized only a few milliliters of fuel was developed (reference 1). Fundamental flame velocities in the region from 30 to 70 centimeters per second were determined by this method. Attempts to measure higher flame velocities, such as those of acetylene-air mixtures, which have a maximum fundamental flame velocity of approximately 150 centimeters per second (references 4 and 5), were unsuccessful. High-speed motion pictures indicated a highly irregular and erratic

flame. Because distortion of high-velocity flames may be due to turbulence generated by the unburned gases, it was considered possible to reduce this turbulence by using a flame tube of smaller diameter. Acetylene was chosen as the test hydrocarbon because flame-velocity data were available in the literature for comparison purposes and because acetylene represents the upper limit of flame velocity for combustible mixtures of hydrocarbon and air. It is desirable to increase the range of flame velocities that can be measured by the tube method to permit the future study of the effect of oxygen enrichment on flame velocity, and to permit a study of nonhydrocarbons of high flame velocity but limited availability.

This report contains a discussion of the flame-tube geometry changes necessary to extend the flame-velocity range of the tube method as well as a discussion of the effect of these changes on the experimentally measurable quantities. The flame velocity of acetylene is compared with the hydrocarbons previously studied and with the burning velocity of acetylene-air flames obtained by other investigators.

APPARATUS AND PROCEDURE

Apparatus. - A schematic diagram of the experimental apparatus is shown in figure 1. It is identical to that previously reported (reference 1) except for a change in the geometry of the flame tube. The internal diameter was decreased from 25 to 12.5 millimeters. The length and the orifice diameter at the ignition end of the flame tube remained the same as before. The orifice at the other end of the flame tube consisted of a glass tube bent at right angles with the open end facing downward and had a gradually increasing internal diameter from 1.7 to 6 millimeters.

Procedure. - The experimental procedure was the same as that described previously (reference 1). A gaseous, combustible mixture of known composition, consisting of pure acetylene (C.P. grade) and dried air, was prepared and introduced into the evacuated, Pyrex, horizontal, cylindrical flame tube and ignited with a small methyl alcohol flame.

The linear or spatial observed flame velocity U_O is the velocity component normal to the cross-sectional plane of the flame tube. It is a function of hydrocarbon type and concentration and is dependent on the geometry of the experimental apparatus. The linear flame velocity was measured at room temperature and atmospheric pressure by means of two photocells placed at a distance of 13 centimeters apart and connected to an electronic timer. The uniformity of flame travel in the portion of the flame tube between the two photocells was confirmed by the rotating drum camera method reported in reference 1.

The fundamental flame velocity U_f is defined as the velocity component normal to any tangent to the flame surface. It is a function of hydrocarbon type and concentration and is independent of the geometry of the experimental apparatus. It was calculated by the equation (reference 1)

$$U_f = (U_0 - U_g) \frac{A_t}{A_f} \quad (1)$$

where

U_f fundamental flame velocity

U_0 linear flame velocity

U_g gas velocity ahead of flame

A_t cross-sectional area of flame tube

A_f flame surface area

The mean gas velocity ahead of the advancing flame U_g was evaluated as previously described (reference 1) from the volumetric flow rate determined from photographs of a soap bubble blown by the moving gas. The volumetric flow rate divided by the cross-sectional area of the flame tube yields the gas velocity. In order to simplify the experimental procedure, shadow photography was employed instead of direct photography. Because the rate of gas expansion is greater for high-velocity flames than for low-velocity flames, high-speed photography was used.

A 25-watt, zirconium concentrated-arc lamp served as a point source of light. The light source was placed at a distance of 41 inches from a 3-inch diameter, 27-inch focal length, convergent lens. The light passed through the 3-inch lens, through a right-angled soap-bubble tube placed 2 inches from the lens, and into the 2-inch lens of a high-speed motion-picture camera. The camera was at the point of light convergence, 61 inches from the 3-inch lens. Two 12-volt storage batteries connected in series provided the power necessary to operate the camera at the desired film speed of approximately 600 frames per second.

Similarly, the flame was photographed with a high-speed motion-picture camera at a film speed of approximately 600 frames per second and the surface area was calculated from the photographs.

The cross-sectional area of the precision-bored flame tube A_t was obtained by direct measurement of the internal diameter and is accurate to ± 0.5 percent.

RESULTS AND DISCUSSION

Gas flow and spatial flame velocity. - Attempts to obtain reproducible flame-velocity results with acetylene-air mixtures in the 25-millimeter internal diameter flame tube were unsuccessful. High-speed motion pictures indicated nonuniformity of flame travel and a highly irregular and erratic flame shape. Spatial flame velocities as high as 650 centimeters per second were recorded. The irregular appearance of the acetylene flame was attributed partly to turbulent gas flow ahead of the advancing flame and was borne out by a calculated value of 2315 for the Reynolds number, employing the expression (reference 6)

$$R = \frac{\rho U_g D}{\mu} \qquad (2)$$

where

R Reynolds number

ρ gas density

U_g gas velocity

D flame-tube diameter

μ gas viscosity

Calculation of the Reynolds number was made by computing a gas velocity based on the experimental spatial flame velocity and the empirical linear relation between gas and spatial flame velocities previously reported (reference 1), by using the density of dry air at room temperature and atmospheric pressure (reference 7, p. 1625) and by using the viscosity of air at room temperature (reference 7, p. 1656). The following values were used in this calculation:

Spatial flame velocity, U_0, cm/sec	650
Gas velocity, U_g, 0.236 U_0 - 10.47, cm/sec	143
Density of dry air at 25° C and 760 mm of Hg, ρ, g/cu cm	1.185×10^{-3}
Viscosity of air at 25° C, μ, poises	0.183×10^{-3}
Flame tube diameter, D, cm	2.5
Reynolds number, R	2315

In order to extend the tube method to include high-velocity flames, a reduction in the Reynolds number of the gas flow ahead of the flame was essential. This reduction was accomplished by a decrease in the magnitude of two of the variables in the numerator of equation (2); namely, tube diameter and gas velocity. It is evident from equation (2)

that a reduction in the flame-tube diameter, keeping the other variables constant, results in a decrease of the Reynolds number. Therefore, by experimentally decreasing the internal diameter of the flame tube from 25 to 12.5 millimeters the Reynolds number was halved from the previously calculated value of 2315 to 1158 and thus placed the gas flow within the laminar region. As a consequence, smooth flames traveling at lower spatial velocities replaced the previous turbulent flames of high spatial velocity. Because the laminar gas velocity is a linear function of the spatial flame velocity (reference 1), it is obvious that a decrease in gas velocity results with the smooth flames of lower spatial velocity. This further decreases the magnitude of the Reynolds number to a value considerably less than 1158. The experimental values of the gas velocity for various linear observed flame velocities in the 12.5 millimeter flame tube are shown in the following table:

Spatial flame velocity U_0 (cm/sec)	Gas velocity U_g (cm/sec)
347	71.8
358	72.6
367	73.7
389	75.7

Each of the four values of the spatial flame velocity represents the average of three determinations with a precision of ±2 percent. Two gas velocity calculations were made for each determination. Each of the four values of the gas velocity thus represents an average of six calculated values with a precision of ±4 percent. Such relatively poor precision can be tolerated because a very small effect on the final calculated value of the fundamental flame velocity is produced. Linear extrapolation of the data to a maximum spatial flame velocity of 392 centimeters per second yields a maximum gas velocity of 76 centimeters per second. Substitution of this maximum gas velocity value into the expression for the Reynolds number (equation (2)), employing values for the density and viscosity of air as before and using the new diameter of 12.5 millimeters, gives a calculated Reynolds number of 615, which places the gas flow well within the laminar region.

The empirical linear relation between the laminar gas velocity and the spatial flame velocity over a range of spatial flame velocities from 70 to 150 centimeters per second was experimentally established in the 25-millimeter flame tube (reference 1) and was represented by the expression

$$U_g = 0.236\, U_0 - 10.47 \qquad (3)$$

When the experimental laminar gas-velocity results obtained with acetylene in the 12.5-millimeter flame tube are combined with those obtained for other hydrocarbons in the 25-millimeter flame tube (reference 1) and the method of least squares is applied, a more accurate empirical linear relation over a range of spatial flame velocities from 70 to 400 centimeters per second is obtained and represented by the expression

$$U_g = 0.228\ U_0 - 9.67 \qquad (4)$$

Both relations are shown in figure 2. Combining the gas velocity data, as shown by the solid curve in figure 2, does not show conclusively that the empirical relation between the gas velocity and spatial flame velocity is independent of flame-tube diameter. The purpose of arbitrarily combining the data was to simplify the experimental results. Use of either relation produces no significant changes in the values previously calculated for the Reynolds number. In addition, a comparison of the effect of the two relations on the final calculated value of the fundamental flame velocity shows a difference of less than 1 percent within the ranges of spatial and gas velocity depicted.

The smooth relation obtained in the 12.5-millimeter flame tube between the spatial flame velocity and the concentration of acetylene, expressed as a fraction of stoichiometric, is presented in figure 3. At least three determinations of the linear flame velocity were made for each mixture concentration studied. The flame velocities depicted are average values and have a precision of ±2 percent. The maximum spatial flame velocity of 392 centimeters per second occurs at the approximate stoichiometric fraction of 1.34. Within the ranges of concentration and flame velocity shown, smooth and constant flame shapes were photographically observed, which confirms the belief that turbulent gas flow ahead of the flame was responsible to a large extent for the irregular flame shapes found in the 25-millimeter flame tube.

Flame surface area. - In the present investigation of the tube method, with the assumption that equation (1) is an exact expression, there is a strong limitation to the calculation of absolute values of fundamental flame velocity. The greatest limiting factor is the uncertainty of the absolute value of the flame surface area. Coward and Hartwell (reference 8) calculated the flame surface area based on the assumption that the flame approximated a semiellipsoid. This assumption was modified slightly in reference 1. However, recent examination of the flame geometry has indicated the Coward and Hartwell assumption to be a good one, as shown in the following discussion.

Theorems from analytical geometry (reference 9) define a diameter of a conic as the straight line locus of the middle points of any system of parallel chords. The point of intersection of any two diameters is the center of the conic. It was found from the flame photographs that

the center point varied, depending on where the parallel systems of chords were drawn. It was therefore concluded that the planar flame trace is not a true conic. Thus, the flame surface is not a true semiellipsoid since any planar cross section of a true semiellipsoid is a semiellipse.

An attempt was then made to ascertain in a qualitative manner the extent of the deviation of the flame trace from that of a semiellipse. The result is shown in figure 4 where the dashed and solid curves represent the magnified flame trace and the semiellipse, respectively. Based on this one planar comparison, the flame approximates a true semiellipsoid fairly closely. The semiellipse was constructed by a standard procedure (reference 10). The points where the flame first touches the top and bottom of the flame tube were joined by a line. The midpoint of this line was taken as the center point in the construction of an inscribed and a circumscribed circle. The coordinate axes thus consisted of the diameters of the circles. Points on a semiellipse were then plotted and a curve drawn through the points.

The Coward and Hartwell equation for calculating the flame surface area is represented by the expression (reference 8)

$$A = \pi b' \left[(a'^2 - c'^2)^{\frac{1}{2}} E(K,\varphi) + c'^2 (a'^2 - c'^2)^{-\frac{1}{2}} F(K,\varphi) \right] + \pi c'^2 \quad (5)$$

where

A	flame surface area
$a' > b' > c'$	ellipsoid semiaxes
$E(K,\varphi)$	complete elliptic integral of second kind
$F(K,\varphi)$	complete elliptic integral of first kind
φ	$\sin^{-1} e$
K	e'/e
e	eccentricity in plane of axes a' and c', $\frac{(a'^2 - c'^2)^{\frac{1}{2}}}{a'}$
e'	eccentricity in plane of axes b' and c', $\frac{(b'^2 - c'^2)^{\frac{1}{2}}}{b'}$

Coward and Hartwell (reference 8) selected the axes to be a line joining the points where the flame first touches the top and bottom of the flame tube and twice the perpendicular distance between the above mentioned line and the point most remote from it located on the flame trace. The third axis is the tube diameter. Whereas these lines are true axes of the ellipsoid they are not the major and minor axes usually considered and hence the complex equation (5) is necessary to calculate the surface area. This computation is extremely time consuming when a large number of flames is being studied. A simplified procedure for computing the flame surface area is therefore suggested. The simplified procedure employs the method used to construct an ellipse that was described previously. The diameters of the inscribed and circumscribed circles used to construct the ellipse are the minor and major axes, respectively, the flame-tube diameter again being the third axis of the ellipsoid. A comparison of the axes chosen by both methods is illustrated in figure 5. The Coward and Hartwell axes are represented by a' and c' of figure 5(a) whereas the axes chosen in this investigation are a and c of figure 5(b). The remainder of the ellipse is shown as a dotted line. The major uncertainty of both methods is the estimation of the two points where the flame becomes tangent to the flame tube.

An approximate equation using the axes employed herein (fig. 5(b)) can be derived by a simple infinitesimal-volume-increment method. If the volume of an ellipsoid is represented by the expression

$$V = \frac{4\pi}{3} abc \tag{6}$$

where

V volume of ellipsoid

a,b,c ellipsoid semiaxes

then an infinitesimal volume increment can be represented by the expression

$$dV = \frac{4\pi}{3}\left[ab(dc) + bc(da) + ac(db)\right] \tag{7}$$

where

dV infinitesimal volume increment

$(dc),(da),(db)$ infinitesimal axes increments

If the approximation $(dc) = (da) = (db) = h$ is used, then the area of an ellipsoid can be represented by the expression

$$A = \frac{dV}{h} = \frac{4\pi h(ab + bc + ac)}{3h} \tag{8}$$

$$A = \frac{4\pi}{3}(ab + bc + ac) \tag{9}$$

where

A area of ellipsoid

a,b,c ellipsoid semiaxes

The area of a semiellipsoid can therefore be approximated by the expression

$$A_f = \frac{A}{2} = \frac{2\pi}{3}(ab + bc + ac) \tag{10}$$

where

A_f flame surface area

a radius of circumscribed circle

b radius of flame tube

c radius of inscribed circle

It has previously been shown (reference 1) that by following the Coward and Hartwell assumption and construction technique a constant value was calculated for the flame surface area irrespective of hydrocarbon type and concentration over a narrow range of concentrations near the maximum flame speed. Superposition of flame photographs upon a standard flame tracing has shown the flame-front shape between the points where the flame first touches the top and bottom of the flame tube to be constant, also. The constancy of the absolute flame surface area may be ascertained by repeated application of the approximate equation for calculating the area of a semiellipsoid together with the superposition technique previously mentioned for noting the constancy of deviation between assumed and actual flame shapes. Application of equation (10) and the superposition technique to flames of propyne and 2-methylpropane-1-d, photographed in the 25-millimeter flame tube, showed a constant flame surface area. These fuels were chosen because a wide range of spatial flame velocity was represented. The calculated value of the flame surface area was 13.0 square centimeters as compared with a value of 13.1 square centimeters obtained with the Coward and Hartwell equation (reference 1). The difference in calculated flame surface areas is therefore small enough to permit the use of either equation with the same degree of certainty.

Whereas the flame area has been found to be constant from fuel to fuel for concentrations near maximum flame velocity, the calculated value of the flame surface area will depend on the geometric figure chosen as well as the method used to construct the figure from the flame photograph. Values for the maximum fundamental flame velocity of a number of hydrocarbons (references 1 to 3) based on the flame surface-area value quoted in reference 1 are in as good agreement with Bunsen burner values as are different investigators, employing the burner method, among themselves. Therefore, the surface area of reference 1 has been used as a standard for subsequent calculations.

Application of equation (10) and the superposition technique to acetylene flames photographed in the 12.5-millimeter flame tube over a concentration range from 8.05 to 11.71 percent by volume showed a constant flame surface area within ±3 percent. The calculated value of the flame surface area for the 12.5-millimeter flame tube was one-fourth of that found in the 25-millimeter flame tube. In addition, the shape of the flame front was found to be the same for flames in both tubes. It thus follows that the ratio of tube cross-sectional area to flame surface area is the same constant for both flame tubes and is equal to 0.451 (reference 1).

Fundamental flame velocity. - The fundamental flame velocity of acetylene is presented as a function of hydrocarbon concentration (expressed as fraction of stoichiometric) in figure 6. At least three determinations of the linear flame velocity were made for each mixture concentration studied. The flame velocities depicted are average values and have a precision of ±2 percent. The maximum fundamental flame velocity of 141 centimeters per second occurs at an approximate stoichiometric fraction of 1.34.

A previous plot (reference 1, fig. 13) of the maximum fundamental flame velocity as a function of the number of carbon atoms in the straight chain for a number of the normal aliphatic hydrocarbons is shown in figure 7 with acetylene added. Acetylene has the highest flame velocity of all hydrocarbons previously reported. It has a peak flame velocity approximately 100 percent greater than that of propyne, the hydrocarbon with the second highest flame velocity.

A comparison of the maximum fundamental flame velocity of acetylene reported herein with values quoted in the literature (references 4 and 5) is presented in the following table:

Source	Maximum fundamental flame velocity of acetylene (cm/sec)
This research	141
Reference 4	150
Reference 5	157

The value here is practically in as good agreement with the literature values as they are between themselves.

The value for the maximum fundamental flame velocity of acetylene reported herein is consistent with results obtained previously for other hydrocarbons (references 1 to 3). This consistency is illustrated in figure 8 where the maximum fundamental flame velocity obtained for some hydrocarbons (references 1 to 3), including acetylene, is plotted against the maximum fundamental flame velocity reported for the same hydrocarbons in reference 5. The acetylene comparison point is consistent with the correlation of the two sets of flame-velocity data.

SUMMARY OF RESULTS

The following results were obtained in this investigation:

1. The tube method for determining fundamental flame velocities was extended to include flame velocities of at least 141 centimeters per second by reducing the diameter of the flame tube. This reduction decreased the Reynolds number of the unburned gas ahead of the flame from a turbulent to a laminar region.

2. The linear relation between laminar gas velocity and spatial flame velocity was experimentally extended to spatial flame velocities in the region of 400 centimeters per second. This relation fits the empirical linear relation between the gas velocity and spatial flame velocity previously obtained in the 25-millimeter flame tube.

3. Geometrical analysis of flame photographs showed the flame to approximate a semiellipsoid very closely.

4. An approximate method of computing flame surface area was found to be in good agreement with the Coward and Hartwell method.

5. The ratio of tube cross-sectional area to flame surface area was found to be the same constant in the 25- and 12.5-millimeter flame tubes.

6. The maximum fundamental flame velocity of acetylene was found to be 141 centimeters per second, which is consistent with results previously reported for other hydrocarbons.

CONCLUSION

The results obtained with acetylene indicate that the tube method can be extended to include fundamental flame velocities of at least 141 centimeters per second.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio.

REFERENCES

1. Gerstein, Melvin, Levine, Oscar, and Wong, Edgar L.: Fundamental Flame Velocities of Pure Hydrocarbons. I - Alkanes, Alkenes, Alkynes, Benzene, and Cyclohexane. NACA RM E50G24, 1950.

2. Levine, Oscar, Wong, Edgar L., and Gerstein, Melvin: Fundamental Flame Velocities of Pure Hydrocarbons. II - Alkadienes. NACA RM E50H25, 1950.

3. Gerstein, Melvin, Levine, Oscar, and Wong, Edgar L.: Fundamental Flame Velocities of Hydrocarbons. Paper presented at the 119th meeting of the Am. Chem. Soc. (Cleveland), April 9-12, 1951. (See abstract of Papers Presented before a Joint Symposium on Combustion Chemistry and the Division of Gas and Fuel Chemistry of the Am. Chem. Soc., pp. 333-342.)

4. Linnett, J. W.: Propagation of flame. Fuel, vol. XXIX, 1950, pp. 13-15.

5. Calcote, Hartwell F., Barnett, Charles M., and Irby, Moreland R.: The Burning Velocity of Various Compounds by the Bunsen Burner Method. Paper presented at the 116th meeting of the Am. Chem. Soc. (Atlantic City, N. J.), Sept. 18-23, 1949. (See Abstracts of Papers, 116th meeting of the Am. Chem. Soc., p. 38P.)

6. Dodge, Russell A., and Thompson, Milton J. E.: Fluid Mechanics. McGraw-Hill Book Co., Inc., 1937, p. 182.

7. Anon.: Handbook of Chemistry and Physics, Charles D. Hodgman, ed. Chem. Rubber Pub. Co. (Cleveland), 27th ed., 1943.

8. Coward, H. F., and Hartwell, F. J.: Studies in the Mechanism of Flame Movement. Part II. The Fundamental Speed of Flame in Mixtures of Methane and Air. Jour. Chem. Soc. (London), pt. II, 1932, pp. 2676-2684.

9. Mason, Thomas E., and Hazard, Clifton T.: Analytic Geometry, Ginn and Company, 1927.

10. Oberg, Erik, and Jones, F. D.: Machinery's Handbook. The Industrial Press, 11th ed., 2nd printing, 1942, p. 279.

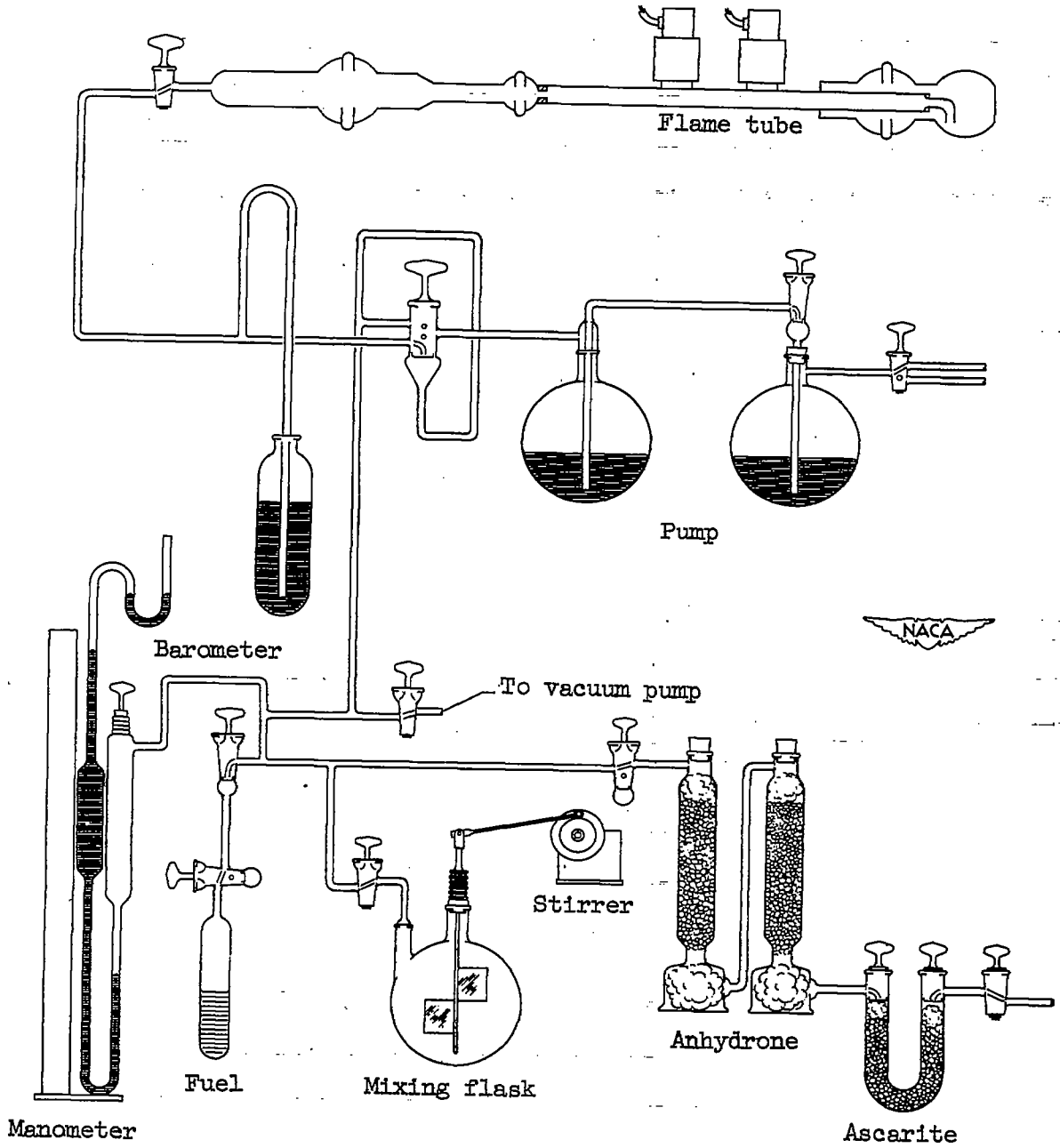


Figure 1. - Flame-speed apparatus.

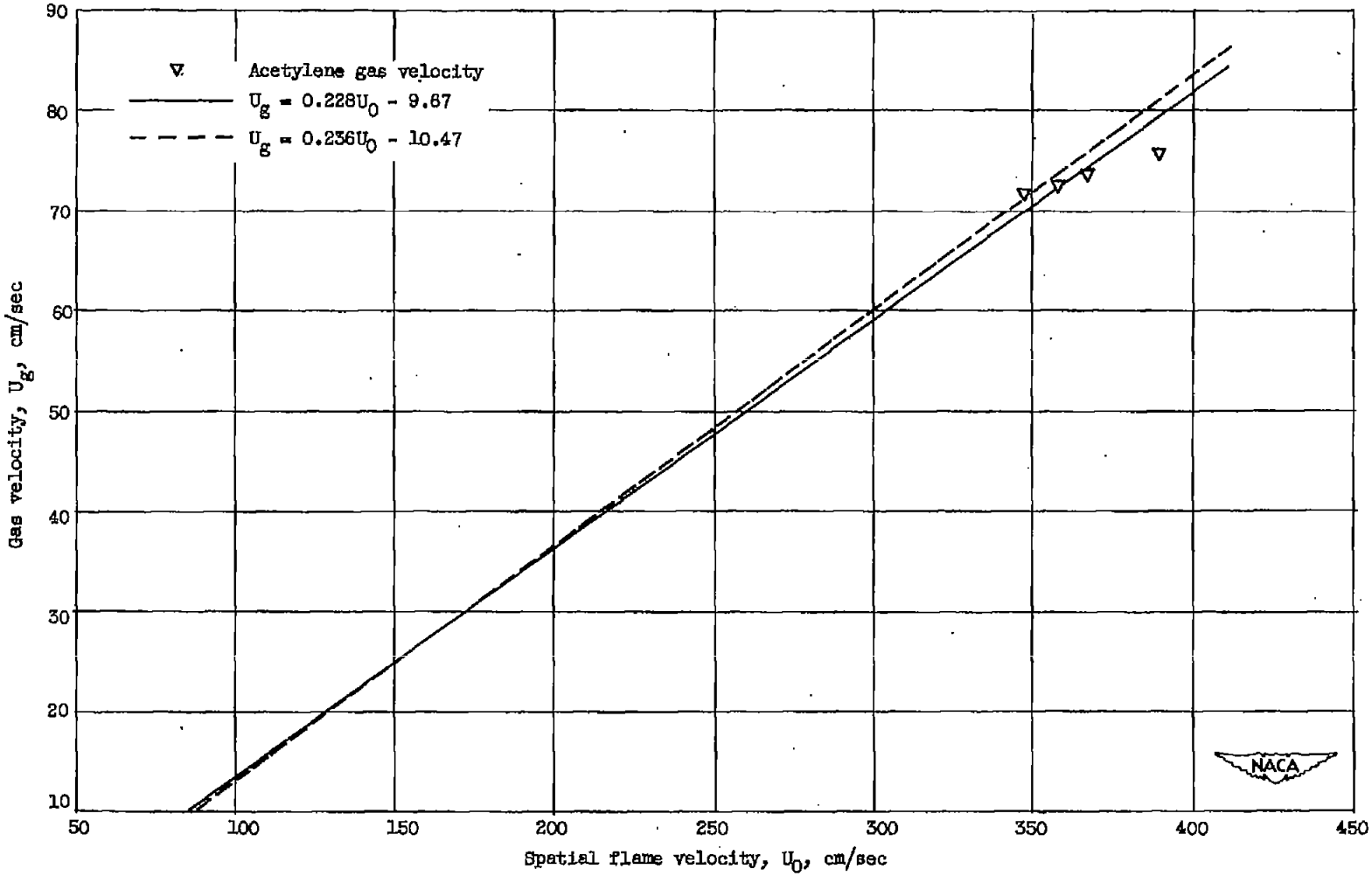


Figure 2. - Variation of unburned-gas velocity with spatial flame velocity.

Figure 3. - Spatial flame velocity of acetylene.

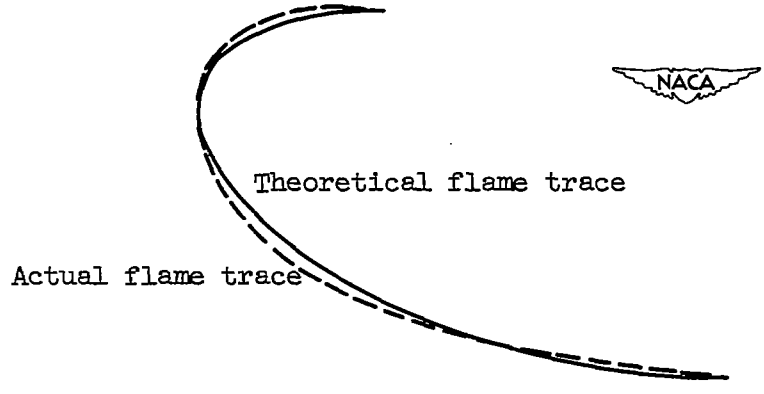
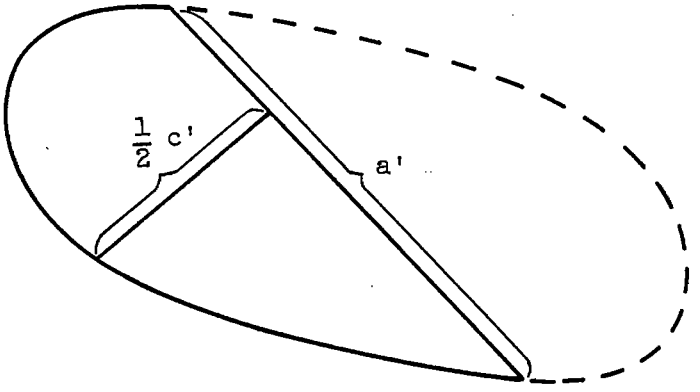
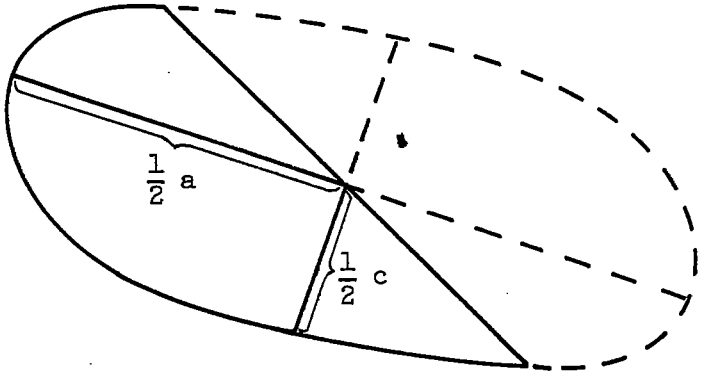


Figure 4. - Comparison of theoretical and actual flame traces.



(a) Coward and Hartwell axes.



(b) Axes from the present investigation.

Figure 5. - Comparison of axes chosen by two construction methods.

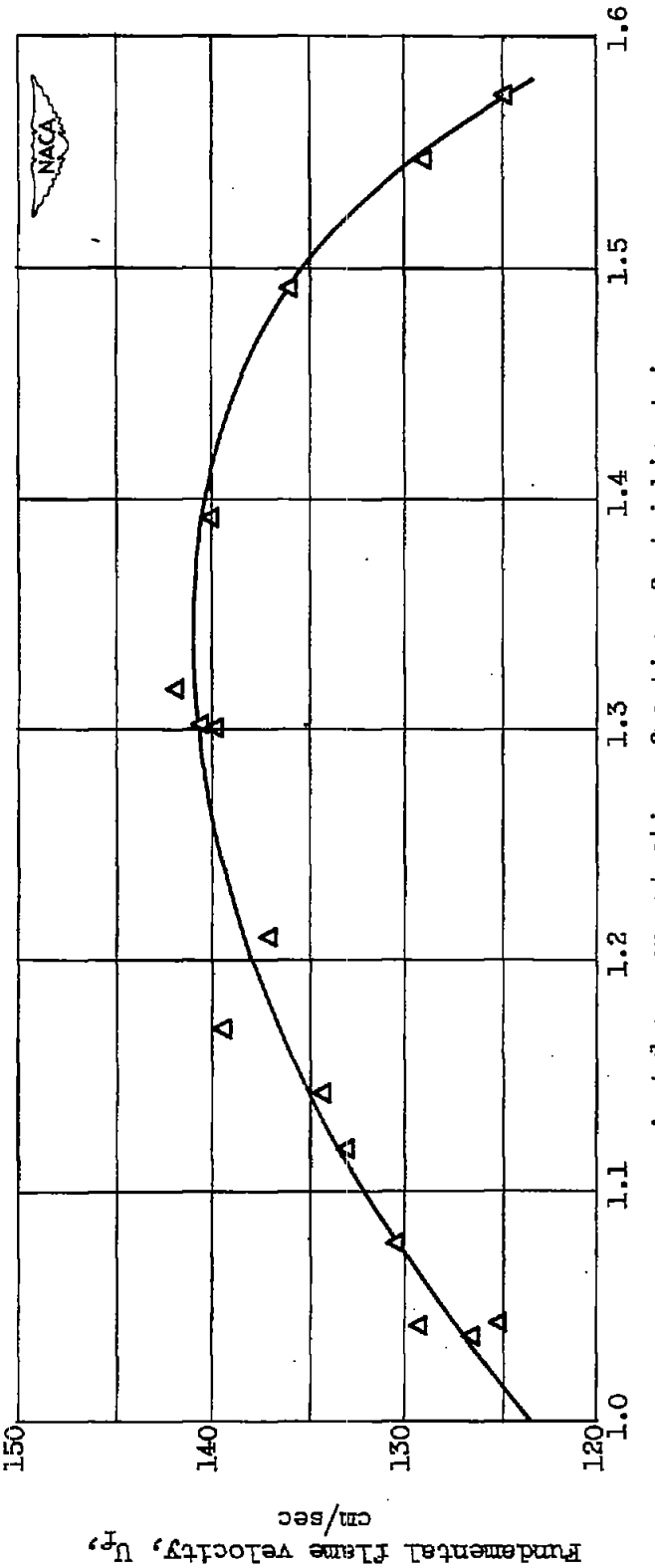


Figure 6. - Fundamental flame velocity of acetylene.

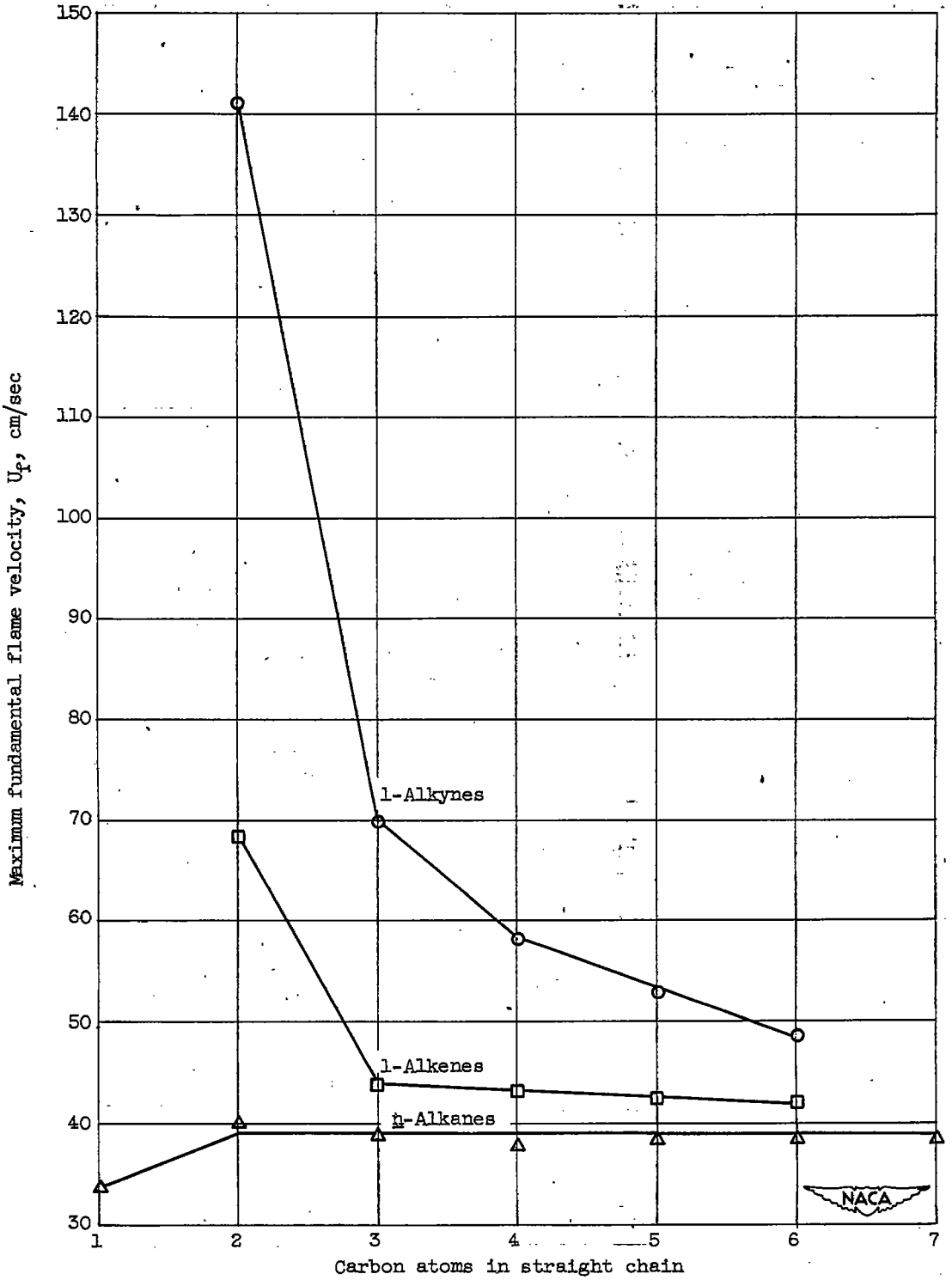


Figure 7. - Summary of maximum fundamental flame velocities of normal aliphatic hydrocarbons.

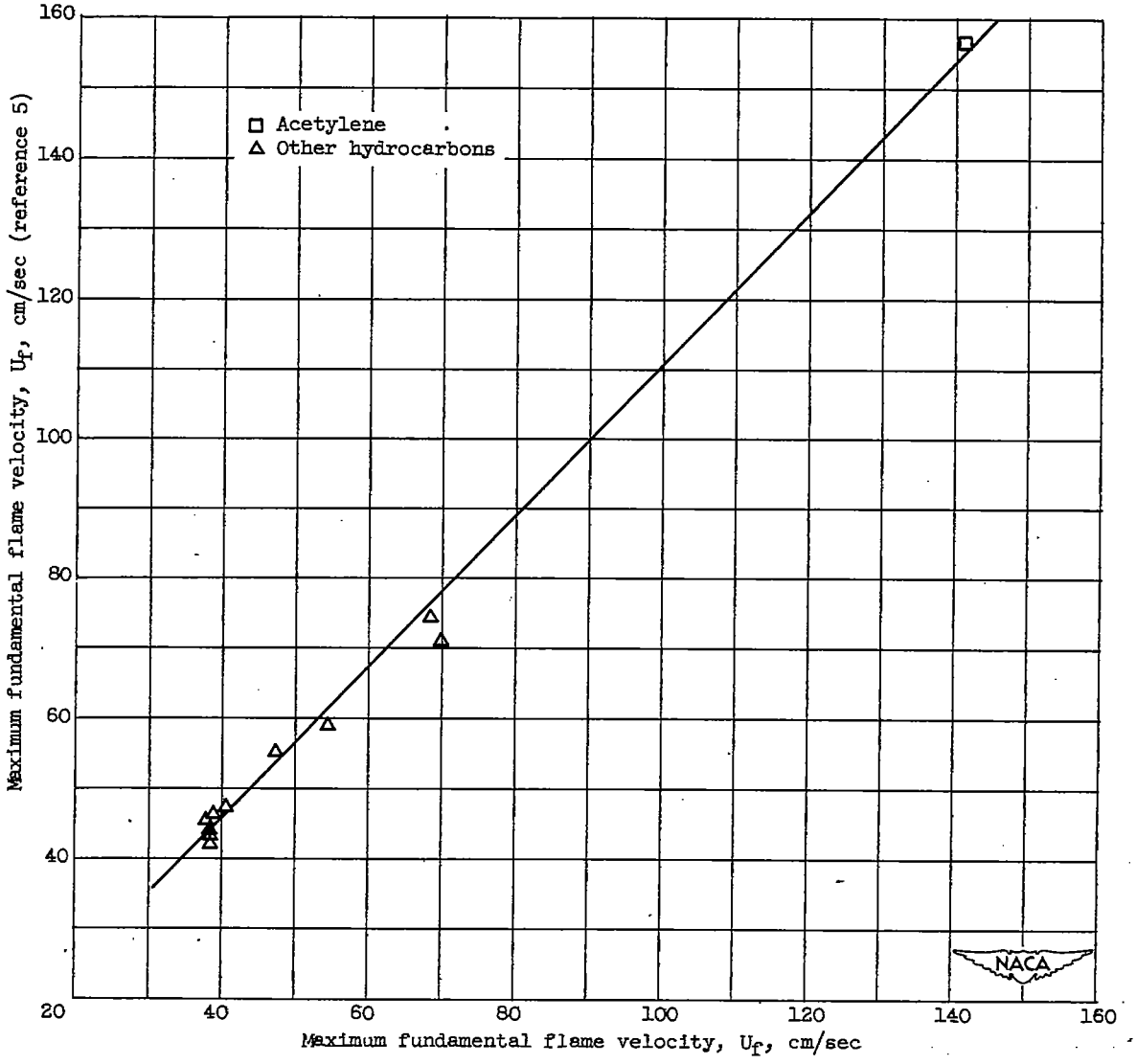


Figure 8. - Comparison of maximum fundamental flame velocity of some hydrocarbons.